Where is the Baseline for Color Transparency Studies with Moderate Energy Electron Beams?*

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Abstract

Study of color transparency (CT) effects at moderate energies is more problematic than is usually supposed. Onset of CT can be imitated by other mechanisms, which contain no explicit QCD dynamics. In the case of the $(e, e'p)$ reaction the standard inelastic shadowing well known in the pre-QCD era, causes a substantial growth of nuclear transparency with Q^2 and a deviation from the Glauber model, analogous to what is assumed to be a signal of CT.

In the case of exclusive virtual photoproduction of vector mesons, CT is expected to manifest itself as an increase of nuclear transparency with Q^2 in production of the ground states and as an abnormal nuclear enhancement for the radial excitations. We demonstrate that analogous Q^2-dependence can be caused at moderate energies by the variation of so called coherence length, which is an interference effect, even in the framework of the vector dominance model.

One should disentangle the real and the mock CT effects in experiments planned at CEBAF, at the HERMES spectrometer, or at the future electron facility ELFE.

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1 Introduction

Color transparency phenomenon (CT) is a manifestation of the color dynamics of strong interaction which was predicted to occur in diffractive interaction with nuclei [1, 2, 3], in quasielastic high-p_T scattering of electrons and hadrons off nuclei with high momentum transfer [4, 5], in quasi-free charge-exchange scattering [6, 7]. Unfortunately very few experiments were able to claim confirmation of CT. The most clear signal of CT was observed with high statistics in the PROZA experiment at Serpukhov [8] in quasifree charge-exchange pions scattering off nuclei at 40 GeV (see discussion in [6, 7]). The observation of the onset of CT in Q^2-dependence of nuclear transparency in virtual diffractive photoproduction of ρ-mesons was claimed recently by the E665 collaboration at Fermilab [9]. Unfortunately the statistical confidence level of the signal is quite poor.

The important signature of CT is the rising nuclear transparency (vanishing final state interaction) with increasing hardness of the reaction. However, available experimental facilities do not still allow to reach that kinematical region where a strong signal of CT is expected, but only a onset of of this phenomenon. In such circumstances one should be cautious about effects which may mock a signal of CT. In view of the weakness of the expected signal of CT one has to understand the origin of the "background", i.e. to know what to expect in absence of the CT effect.

In present paper we would like to draw attention to some effects which do not rely upon the QCD dynamics, but can mock the onset of CT. We discuss such effects in quisielastic electron scattering and in electroproduction of vector mesons off nuclei.

2 Q^2-dependence of nuclear transparency in $(e, e'p)$

Recent failure of the NE18 experiment at SLAC [10] to observe the onset of color transparency (CT) in $(e, e'p)$ reaction has excited interest to the baseline for such a study. It was realized that even the Glauber model have a substantial uncertainty. Nevertheless, a nearly Q^2-independent nuclear transparency is expected in the Glauber approximation, what makes it possible to single out the Q^2-dependent effects [4, 5].

We call the Glauber eikonal approximation an approach disregarding any off diagonal diffractive rescatterings of the ejectile, which itself is assumed to be just a proton.

It is known since Gribov's paper [11], that the Glauber model should be corrected for inelastic shadowing at high energies. The very existence and the numerical evaluations of the inelastic corrections (IC) was nicely confirmed by the high precision measurements of the total cross sections of interaction of neutrons [12] and neutral K-mesons [13] with nuclei. Due to IC the total cross section turns out to be smaller, i.e. nuclear matter is more transparent, than is expected in the Glauber approximation. Important for further discussion is the fact that the deviation (IC) from the Glauber model grows with energy. An example is shown in fig. 1. The data for $n - Pb$ total cross section as function of energy are compared with the Glauber approximation corrected or not for the IC, evaluated in [12, 14].
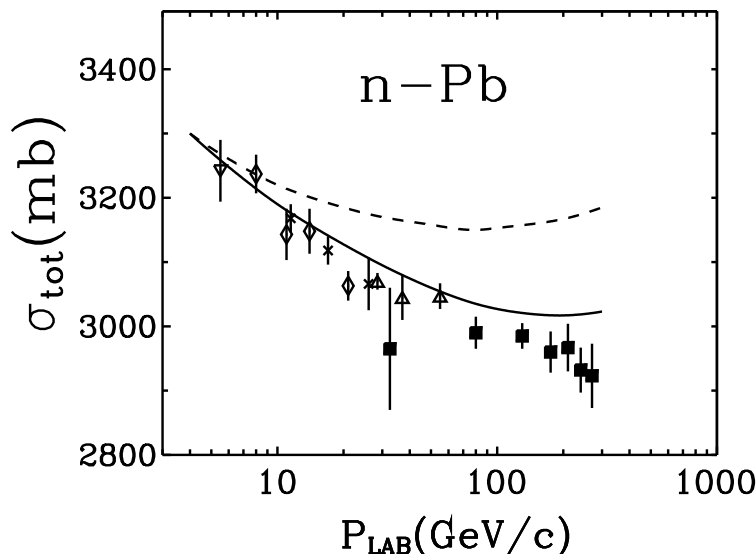

Figure 1: Data on $n - Pb$ total cross section (ref. [12] and references therein). The dashed curve is corresponds to the Glauber approximation. The solid line shows the effect of inclusion of the first order IC to the total cross section as it is calculated in ref. [12]

According to these results one can expect that nuclear matter becomes more transparent at higher ejectile energy, or Q^2 because the energy $\nu = Q^2/2m_N$ correlates with Q^2 within the quasielastic peak. Such a rising Q^2-dependence of the nuclear transparency can imitate

the CT effects [15], which are expected to manifest themselves as a monotonous growth of the nuclear transparency with Q^2 [4, 5].

At this point it worth reminding that CT is a particular case of Gribov's inelastic shadowing, provided that QCD dynamics tunes many elastic and inelastic diffractive rescatterings in the final state to cancel each other [1, 16, 17] at high Q^2. Therefore, one may think that there is no sense in picking up only one IC from many others, which all together build up CT. However, searching for CT effects one should ask himself first of all, what happens if CT phenomenon does not exist; for instance, if the ejectile in $(e, e'p)$ reaction on a bound nucleon is not a small-size wave packet, but is a normal proton. There is a wide spread opinion that the correct answer is provided by the Glauber model. However, the IC shown schematically in fig. 2, makes the nuclear matter more transparent.
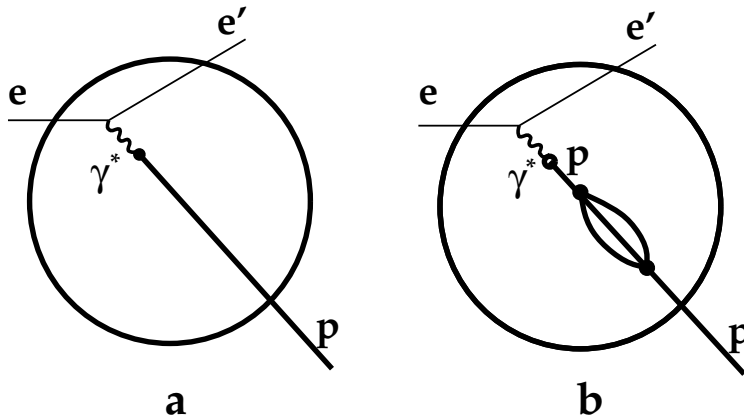

Figure 2: Cartoon showing $A(e, e'p)A'$ reaction with eikonal elastic final state interactions (a) and with diffractive production of inelastic intermediate state (b)

This first order IC corresponds to the diffractive production of inelastic intermediate states by the ejectile proton while it propagates through the nucleus. The proton waves with and without this correction interfere with each other, while the contributions from different production points add up incoherently because the momentum transfer in the $(e, e'p)$ reaction is large. It is important that IC has a positive relative sign, provided that all diffraction amplitudes are imaginary [18, 19, 20]. The resulting nuclear transparency

reads,

$$Tr(Q^2) = \int d^2b \int_{-\infty}^{\infty} dz \rho(b,z) \, \exp[-\sigma_{in}^{NN} \int_{z}^{\infty} dz' \rho(b,z')] \times$$
$$\left[1 + 4\pi \int dM^2 \frac{d\sigma}{dM^2 dt}|_{t=0} \, F_A^2(b,z,q_L)\right]^2 \tag{1}$$

Here b and z are the impact parameter and the longitudinal coordinate of the bound proton which absorbs the virtual photon. σ_{in}^{NN} is inelastic NN cross section. We assume that the $(e,e'p)$ cross section is integrated over the transverse momentum of the ejectile proton relative to the photon direction, and over the missing momentum, which is the difference between the photon and the proton momenta. $T(b) = \int_{-\infty}^{\infty} dz \rho(b,z)$ is the nuclear thickness function. $d\sigma/dM^2 dt|_{t=0}$ is the forward diffraction dissociation cross section in NN interaction. $F_A(b,z,q_L)$ is the nuclear longitudinal form factor [14],

$$F_A(b,z,q_L) = \int_{z}^{\infty} dz' \, \rho(b,z') e^{iz'q_L} \, , \tag{2}$$

where $q_L = (M^2 - m_N^2)/2\nu$ is the longitudinal momentum transfer in the diffraction dissociation. This form factor is of special importance, because it provides the Q^2-dependence of nuclear transparency.

The detailed calculation of an analogous IC to the nuclear total cross section was performed in [12]. We use the same parameterization of the data on $d\sigma/dM^2 dt$ as in [12] and the realistic nuclear density from [21] to calculate expression (1). Following refs. [14, 12, 13] we assume that the inelastic intermediate states attenuate in nuclear medium with the same inelastic cross section as the proton. The predicted growth of nuclear transparency with Q^2 in $Pb(e,e'p)$ is compared in fig. 3 with what is expected to be the onset of CT [22]. We use $\sigma_{in}^{NN} = 33 \, mb$ in order to have the same transparency in the Glauber approximation as in ref. [22]. We see that these two mechanisms, one with and another one without CT dynamics predict about the same magnitude of deviation from the Glauber model up to about $Q^2 \approx 20 \, GeV^2$. It is especially difficult to disentangle the real CT effects and the first-order IC because of a substantial model-dependence of the theoretical predictions for CT. In order to detect reliably a signal of CT one needs Q^2 at least of a few tens of GeV^2,

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where the growth of transparency provided by the first IC saturates at quite a low level.
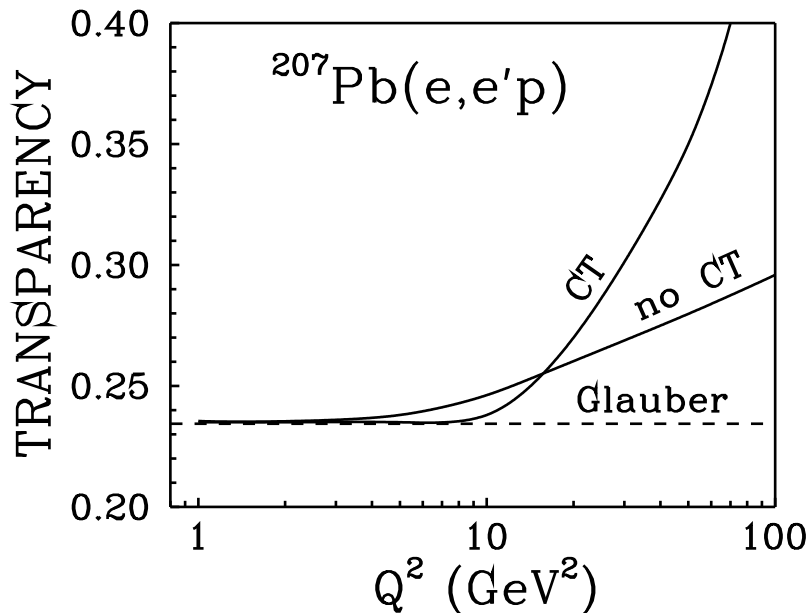

Figure 3: Comparison of the Glauber model (dashed line) with the model [22] incorporating with CT (solid curve – CT) and with our calculation of the first-order IC using eq.(1) (solid curve – no CT)

Our calculations are compared with the data from the NE18 experiment at SLAC [10] in fig. 4. We use a realistic σ_{in}^{NN} from ref. [23] which exhibit a decreasing energy-dependence at low energies (compare with [24]). Of course, more sophisticated calculations may consider the effects of Fermi motion [19, 25, 26], few-nucleon correlations [27, 26, 28, 29, 30], accuracy of the closure approximation [31], etc. We try to escape these complications to make the presentation simpler and clearer. The relative contribution of the IC is expected to be nearly independent of the mentioned above details of nuclear structure.

Note that we predict a bigger effect of inelastic shadowing than that in the total hadron-nucleus cross sections [12, 13]. In the latter case case it is the correction to the small exponential term in the elastic amplitude which is subtracted from unity, while in the present case we deal with a net transparency effect.

To conclude this section, we estimated the first-order IC, which causes a growth of nuclear
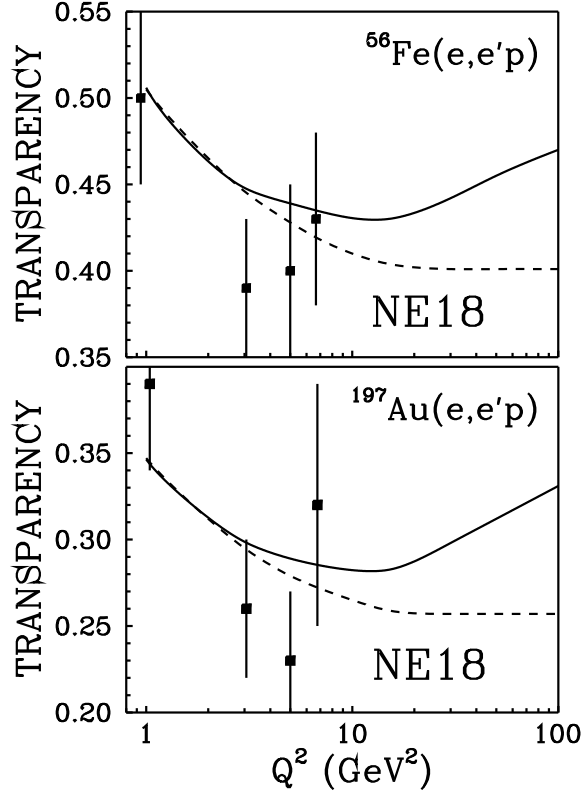
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Figure 4: Comparison of the Glauber model (dashed line) and of the results of our calculations of the standard first-order IC, eq. (1), (solid line) with the data from the NE18 experiment [10]

transparency with Q^2 in quasielastic scattering of electrons off nuclei and can imitate the onset of CT up to $Q^2 \sim 20 \ GeV^2$. The evaluation of this IC is independent of our ideas about QCD dynamics of hard interaction, since it is based only on the data on diffractive dissociation. Although this correction is a part of the total CT pattern, it survives any modification of the underlying dynamics and should be considered as a *baseline* for CT studies. One can reliably disentangle this contribution and the real CT effect only at Q^2 of a few tens of GeV^2, where the former saturates, but CT provides a growth of nuclear transparency up to unity. Note that in order to suppress the IC under discussion, one can use light nuclei, at the expense of a smaller CT effect.

A new possibility to search for CT effect, which is free of the contribution of the IC discussed above, was suggested in [19, 25]. The asymmetry of nuclear transparency relative

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to the longitudinal missing momentum turns out to be sensitive to the QCD dynamics of quasi-elastic electron scattering on a bound nucleon and reflects generic properties of CT. A more realistic evaluation of this effect [32] demonstrates that this is a promising way to detect a CT signal in a high-statistics experiment.

3 Exclusive electroproduction of vector mesons

Electrons are a source of energetic virtual photons. In the reaction of virtual diffractive photoproduction of vector mesons on can control the size of the produced wave packet varying Q^2, but keeping the photon energy fixed. Therefore, the inelastic corrections considered in the previous section are irrelevant, since they are only energy-dependent.

Although the collaboration E665 [9] has observed a signal of CT effects in the exclusive muoproduction of ρ-mesons predicted in [3], one should be cautious with the conclusions. The predictions for Q^2-dependence of nuclear transparency [3] were done for the asymptotically high photon energies. We demonstrate below that variation of the coherence length may imitate to some extend the CT effects.

The vector mesons photoproduced at different longitudinal coordinates have relative phase shifts $\Delta z q_L$ due to the difference in the photon and the meson longitudinal momenta $q_L = (Q^2 + m_V^2)/2\nu$. For this reason only those mesons interfere constructively which are produced sufficiently close to each other: $\Delta z \leq l_c$, where

$$l_c = \frac{1}{q_L} = \frac{2\nu}{Q^2 + m_V^2} \tag{3}$$

is called coherence length.

One can provide this with a space-time interpretation. The photon develops a hadronic fluctuation which can interact with the nucleus during its lifetime $t_c = l_c/c$ (c is the speed of light). If l_c is much shorter than the mean internucleon distance, there is obviously no nuclear shadowing in the initial state. On the other hand, if l_c is much longer than the mean free path of the vector meson in the nuclear medium or the nuclear radius, one cannot any more distinguish between the initial and the final state interactions. Nuclear shadowing is expected in this limit to be the same as in the meson-nucleus interaction. Thus, the energy-

and Q^2-variation of l_c may result in substantial changes in the nuclear shadowing, which can be easily mixed up with the CT effects in some cases [33]. For the light vector meson (ρ, ω, ϕ) production the transition region covers the energies from a few to few tens GeV. For charmonium production the corresponding energy range is an order of magnitude higher.

We demonstrate below how this space-time pattern is realized in the framework of the formal Glauber theory, which does not utilize any space-time development.

3.1   Coherent electroproduction of the ground states off nuclei. Glauber model

We call coherent production the process where the target nucleus remains intact, so all the vector mesons produced at different longitudinal coordinates and impact parameters must add up coherently. This condition substantially simplifies the expression for the photoproduction cross section, which reads [34],

$$Tr^{coh}(\gamma^* A \to V A) = \frac{(\sigma_{tot}^{VN})^2}{4\sigma_{el}^{VN}} \int d^2 b \left| \int_{-\infty}^{\infty} dz \; \rho(b, z) \; e^{iq_L z} \exp\left[-\frac{1}{2}\sigma_{tot}^{VN} \int_z^{\infty} dz' \rho(b, z') \right] \right|^2 \quad (4)$$

We use hereafter the optical approximation for the sake of simplicity, which is quite precise for heavy nuclei.

For numerical calculations we use $\sigma_{tot}^{\rho N} = 25 \; mb$ and $\sigma_{tot}^{\phi N} = 17 \; mb$. The elastic cross section is estimated by means of relation, $\sigma_{el}^{VN} \approx (\sigma_{tot}^{VN})^2/16\pi B^{VN}$, where the slope parameter was fixed at $B^{VN} = 8 \; GeV^{-2}$ and $7 \; GeV^{-2}$ for ρ and ϕ respectively.

The results of calculation of the energy dependence of the nuclear transparency for coherent photoproduction of ρ and ϕ mesons integrated over momentum transfer are plotted in figs. 5 and 6 for different photon virtualities. We see that even the ρ-meson coherent production on medium and heavy nuclei is strongly suppressed at CEBAF energies, but is quite a sizeable effect at energies of HERMES-ELFE.

Since the Q^2-dependence of the nuclear transparency is usually used as a signature for CT, we present in fig. 7 the Glauber model predictions for Q^2-variation of the nuclear transparency in the ρ-meson photoproduction at different photon energies.
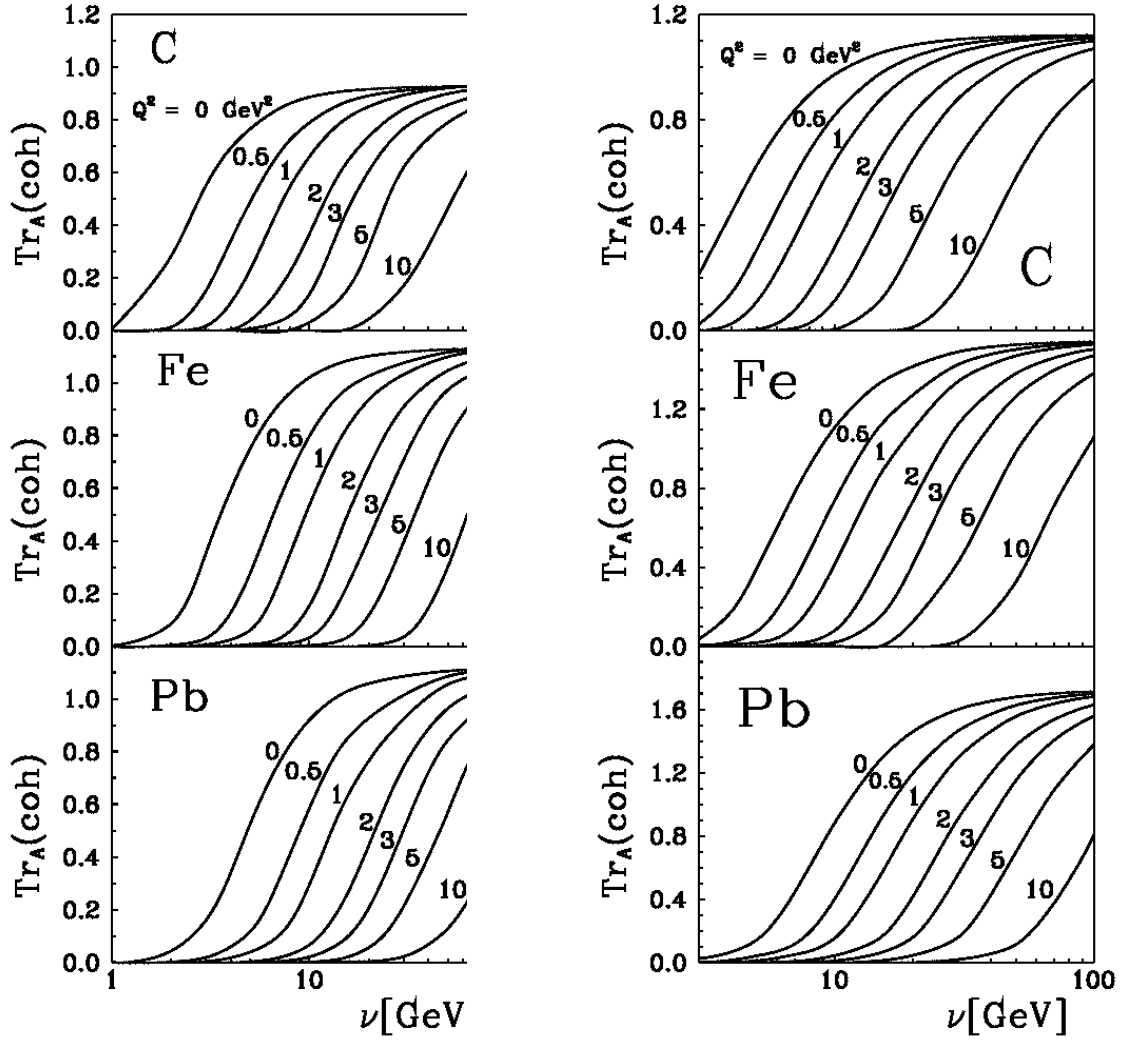
Figure 5: Energy dependence of nuclear transparency in coherent photo-production of ρ-mesons on nuclei versus the photon virtuality, Q^2. The curves are the results of Glauber model calculations using eq. (4)

Figure 6: The same as in fig. 5 but for production of ϕ-mesons

The energy variation of the slopes of differential cross section of coherent photoproduction of ρ and ϕ mesons on iron, $B_{VA} = 1/2\langle b^2 \rangle$, is presented in fig. 8. The condition of coherence results in large values of $B_{VA} \approx R_A^2/3$.

The energy-dependence of the slopes demonstrates a crossing behaviour: $B_{\rho A} < B_{\phi A}$ at low energy, but $B_{\rho A} > B_{\phi A}$ at high energies. This can be understood as follows. At
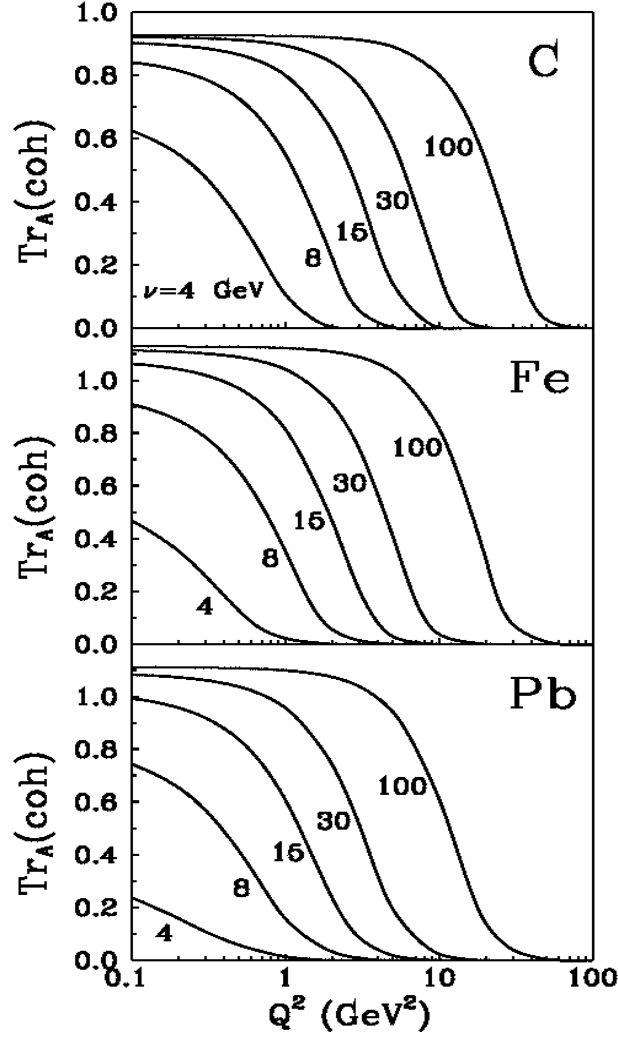
Figure 7: Q^2-dependence of nuclear transparency of coherent photopro-
duction of ρ-meson versus photon energy, calculated with eqs. (5)–(7).
The figures at the curves show values of ν in GeV

high energy the photoproduction cross section is proportional to the elastic one for $V - A$
interaction. In this regime a heavy nucleus is almost black at small impact parameters. At
the same time, the partial elastic amplitude at the nuclear periphery is proportional to the
$V - N$ elastic amplitude, i.e. it is smaller for ϕ than for ρ. This results in a smaller slope
parameter for ϕ than for ρ.

At low energies situation changes, everything is produced on the back surface of the
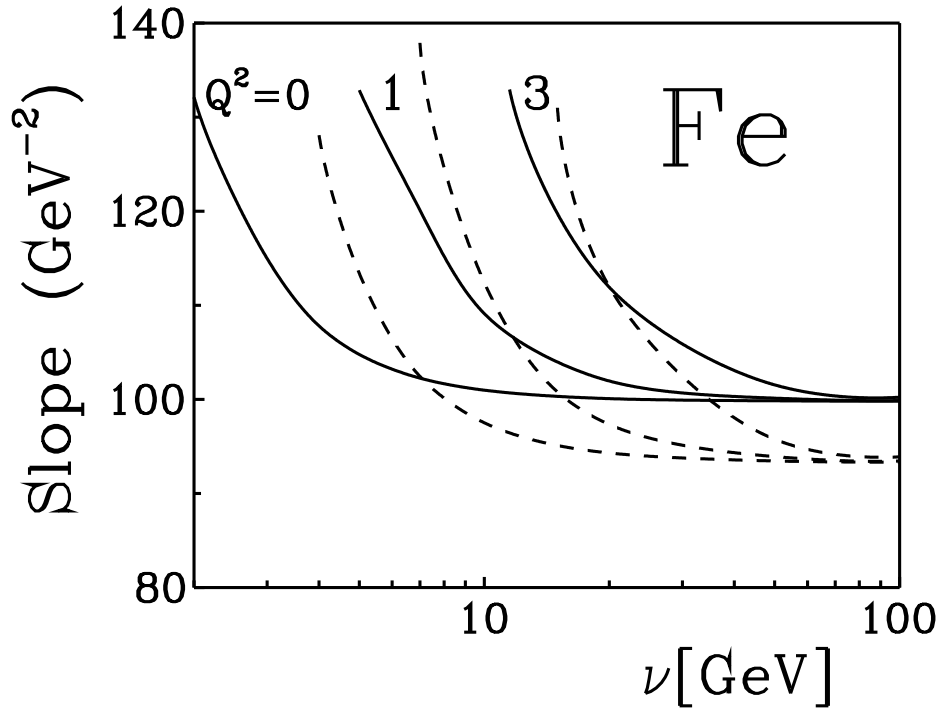
Figure 8: Energy dependence of the slope-parameters for coherent photo-production of ρ (solid lines) and ϕ (dashed lines) vs the photon virtuality, $Q^2 = 0, 1, , 3 \; GeV^2$, shown by figures at the curves.

nucleus. This leads to a rising relative contribution of the nuclear periphery, i.e. to a growth of the slope parameter. Since the mean free path of the ρ is shorter, the contribution of the small impact parameter region is more suppressed, than for the ϕ-meson. Therefore, the ρ slope parameter is larger than that of the ϕ-meson in this energy limit.

3.2 Incoherent electroproduction of the ground states off nuclei

The incoherent diffractive production is associated with a break up of the nucleus, but without production of new particles.

The correct formula for exclusive incoherent electroproduction of vector mesons incor-porating the effects of coherence length is derived for the first time[§] in ref. [35]. The nuclear

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[§]The formula for incoherent photoproduction of vector mesons presented in ref. [34] differs from our eqs. (5)–(7), and we consider it as incorrect. That formula underestimate available data on real photoproduction of ρ off nuclei (see corresponding discussion in ref. [34]). Our calculations nicely agree with the data.

transparency for the cross section integrated over momentum transfer can be represented as a sum of three terms,

$$Tr_{inc}(\gamma^* A \to VX) = Tr_1 + Tr_2 - Tr_{coh} \,, \tag{5}$$

where the first term

$$Tr_1 = \frac{1}{\sigma_{in}^{VN}} \int d^2b \left[1 - e^{-\sigma_{in}^{VN} T(b)}\right] \tag{6}$$

corresponds to the case when the vector meson is produced in both interfering amplitudes on the same nucleon. If those nucleons are different, the corresponding term Tr_2 in eq. (5) reads,

$$Tr_2 = \frac{\sigma_{tot}^{VN}}{2\sigma_{el}^{VN}} (\sigma_{in}^{VN} - \sigma_{el}^{VN}) \int d^2b \int_{-\infty}^{\infty} dz_2 \, 8/GeV \rho(b,z_2) \int_{-\infty}^{z_2} dz_1 \, \rho(b,z_1) \,\times$$
$$e^{iq_L(z_2 - z_1)} \, \exp\left[-\frac{1}{2}\sigma_{tot}^{VN} \int_{z_1}^{z_2} dz\rho(b,z)\right] \exp\left[-\sigma_{in}^{VN} \int_{z_2}^{\infty} dz \, \rho(b,z)\right] \tag{7}$$

Two first terms in eq. (5) correspond to the sum over all final states of the nucleus, including the case when the nucleus remains in the ground state. For this reason the third term is subtracted in eq. (5).

In the low- and high-energy limits eqs. (5)-(7) look much simpler. At low energies q_L is large, what causes strong oscillations and cancellations in eqs. (7), (4). Only the first term in eq. (5) survives, and this can be interpreted as a result of the shortness of the coherence length: the photon penetrates without attenuation deep inside the nucleus and instantaneously produces the vector meson on some of the bound nucleons. Absorption of the meson travelling through the nucleus leads to a suppression of the nuclear transparency.

At high-energies $q_L \approx 0$ and eq. (5) takes the form,

$$Tr_{inc}^{q_L \to 0}(\gamma^* A \to VX) \to \frac{1}{\sigma_{el}^{VN}} \int d^2b \left[e^{-\sigma_{in}^{VN} T(b)} - e^{-\sigma_{tot}^{VN} T(b)}\right] = \frac{\sigma_{Qel}^{VA}}{\sigma_{el}^{VN}} \tag{8}$$

We conclude that the nuclear effects in the high-energy photoproduction of vector meson are the same as in the quasielastic scattering of this meson off the nucleus. This result has a clear space-time interpretation. At high energies the coherence length is long and the photon

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converts into the vector meson long in advance of the interaction. This is usually interpreted in terms of vector dominance model (VDM), however we *did not use* any assumption of VDM.

The results of calculation of nuclear transparency for the ρ and ϕ incoherent photoproduction are plotted in figs. 9 and 10 respectively as a function of the photon energy and virtuality.

We see that eqs. (5)-(7) predict a dramatic decrease of nuclear transparency from low to high energies. The explanation follows from the above space-time interpretation. Namely, the mean length of the path of the meson in the nuclear medium at high energies is about twice as long as at low energies. Therefore, one may expect the nuclear transparency at high energies to be a square of that at low energy. Our results depicted in figs. 9, 10 show that such a simple rule works surprisingly well.

Effects of coherence length for electroproduction of heavy flavoured vector mesons are boosted to a higher energy range. However, they are still important at medium energies for light nuclei. As an example, we show the energy dependence of the incoherent real photoproduction of J/Ψ off beryllium in fig. 11.

Since the coherence length eq. (3) is also a function of Q^2 at fixed energy, the contraction of the coherence length causes a growth of nuclear transparency with Q^2, which should be taken into account if one searches for CT effects. Examples of Q^2-dependence for ρ-meson photoproduction are shown in fig. 12. Nuclear transparency steeply increases and then saturates at high Q^2. It is not easy to disentangle such a growth of nuclear transparency induced by the shrinkage of the coherence length and the CT effects. Naively, one could hope to search for CT effects at higher Q^2, where the Glauber model predicts a saturation of $Tr(Q^2)$. However, the nuclear transparency cannot reach unity at this energy, even in the presence of the CT effects. $Tr(Q^2)$ saturates at about the same level as is shown in fig. 12 both with and without CT effects. Indeed, the predicted saturation signals that the coherence length becomes negligibly short. In this situation there is no room for the full CT effect, which needs a destructive interference of all the intermediate states up to the masses of the order of Q. In a simplified way this can be interpreted as a result of the fast
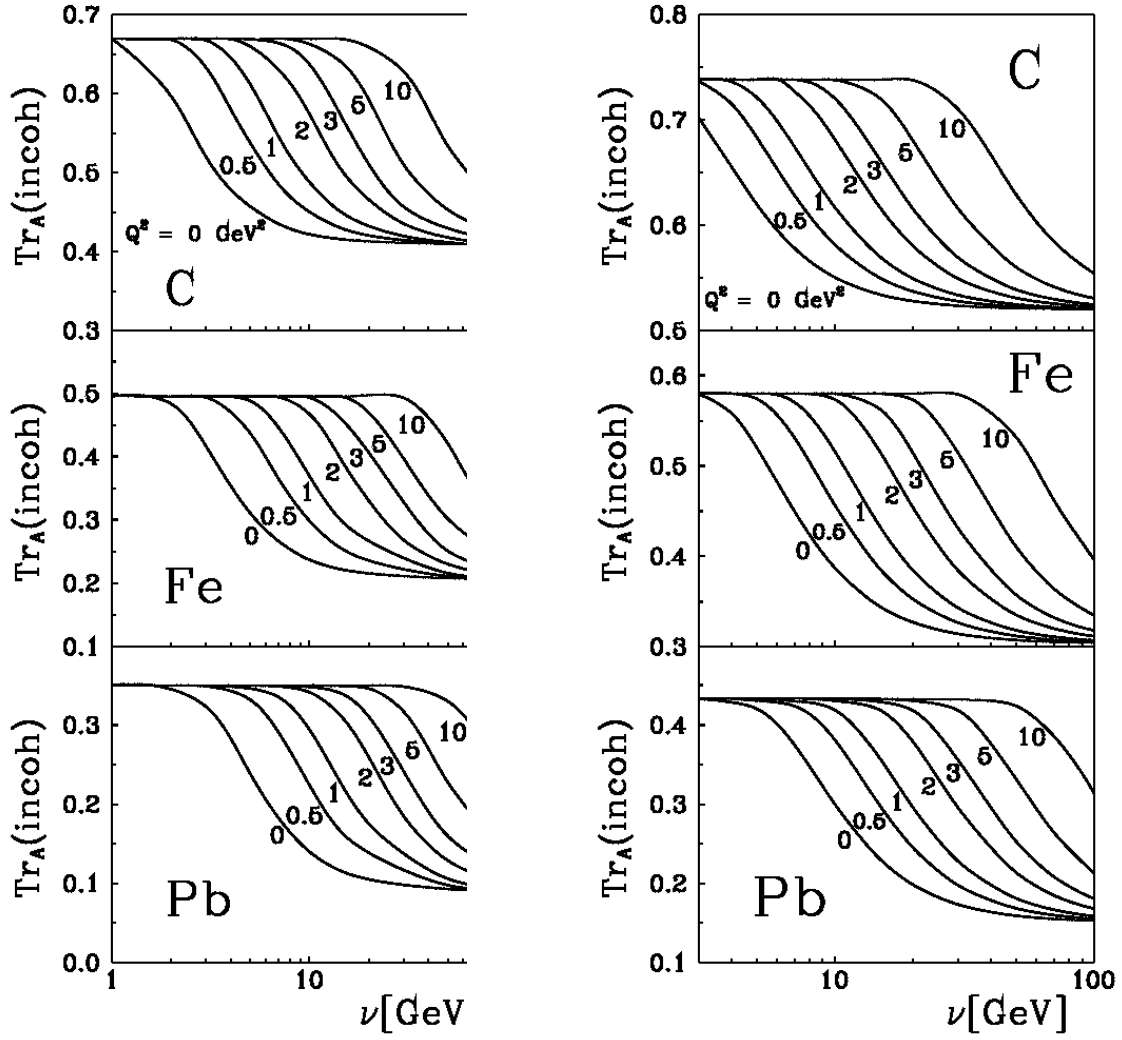
Figure 9: Energy dependence of nuclear transparency for incoherent pho-
toproduction of ρ-mesons on nuclei at different values of Q^2, calculated
with eqs. (5)-(7)

Figure 10: The same as in fig. 9 but for production of ϕ-mesons

expansion of the produced small-size $\sim 1/Q$ wave packet up to a certain size, which depends
on the photon energy, rather than on Q^2.

The importance of the variation of the coherence length is demonstrated in fig. 13 for the
ϕ photoproduction at $\nu = 8\ GeV$ in comparison with the results of ref. [36] which neglected
the coherence length. Despite the smallness of the ϕ absorption cross section, the coherence
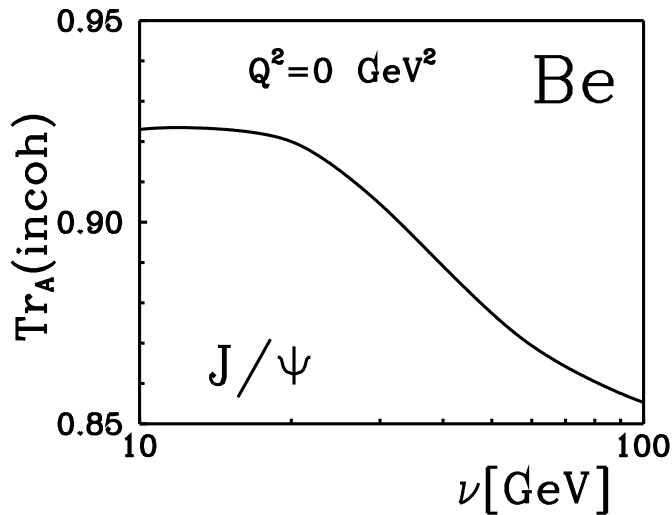
Figure 11: Energy-dependence of nuclear transparency in the incoherent real photoproduction of J/Ψ on beryllium, as calculated with eq. (5)-(7)

length effects are substantial. Some difference between our and ref. [36] predictions at high Q^2 is caused by the difference in the parameters for the nuclear density (we use the parameters from [21]), what, however, does not affect the Q^2-dependence.

It is interesting that even the data from the E665 experiment [9] corresponding to mean energy $\langle \nu \rangle = 138\ GeV$ are affected by the variation of the coherence length. Our Glauber model predictions for incoherent photoproduction of the ρ is shown by the bottom solid curve in fig. 14 in comparison with the E665 data. We predict a dramatic rise of $Tr(Q^2)$ at high Q^2. However, the small-Q^2 data seem to grow faster than our curve, and they are consistent with the predicted [3] effect of CT.

In these circumstances the coherent production of vector mesons is maybe a better way of searching for CT, since the Glauber model predicts a decreasing Q^2-dependence of the nuclear transparency as is shown by the upper solid curve in fig. 14. Observation of a rising $Tr(Q^2)$ would be a convincing signal of CT. The data are consistent with the dashed curve [3], which incorporates the CT effects.

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4 Electroproduction of the radial excitations

As far as it concerns the photoproduction of the radial excitations V', one cannot anymore interpret it on the basis of the Glauber eikonal approximation. Indeed, there are two graphs
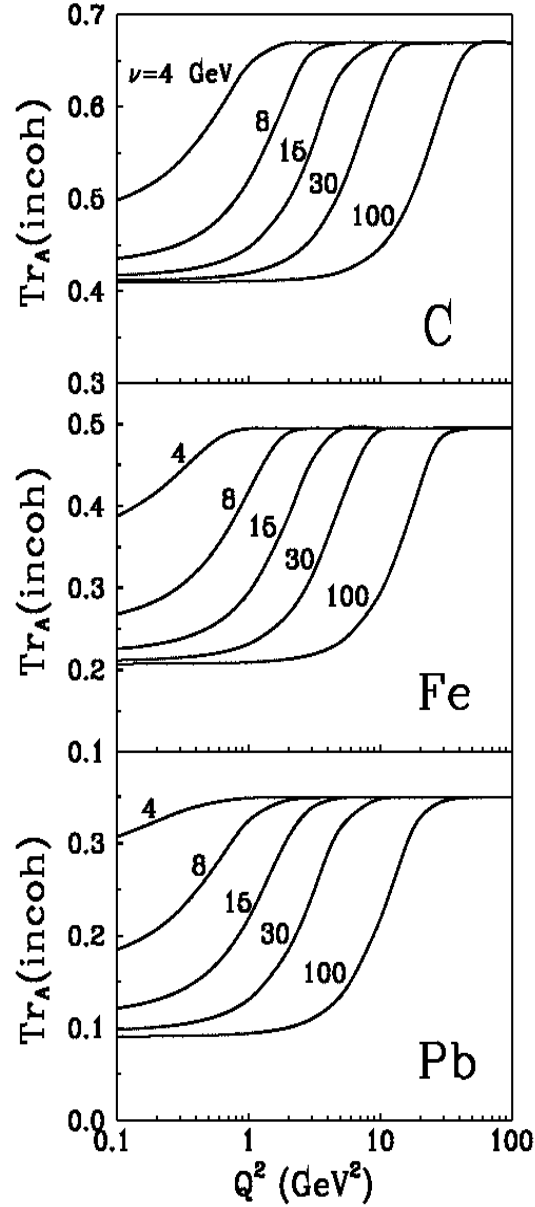

Figure 12: Q^2-dependence of nuclear transparency for incoherent photo-production of ρ-meson at different photon energies ν
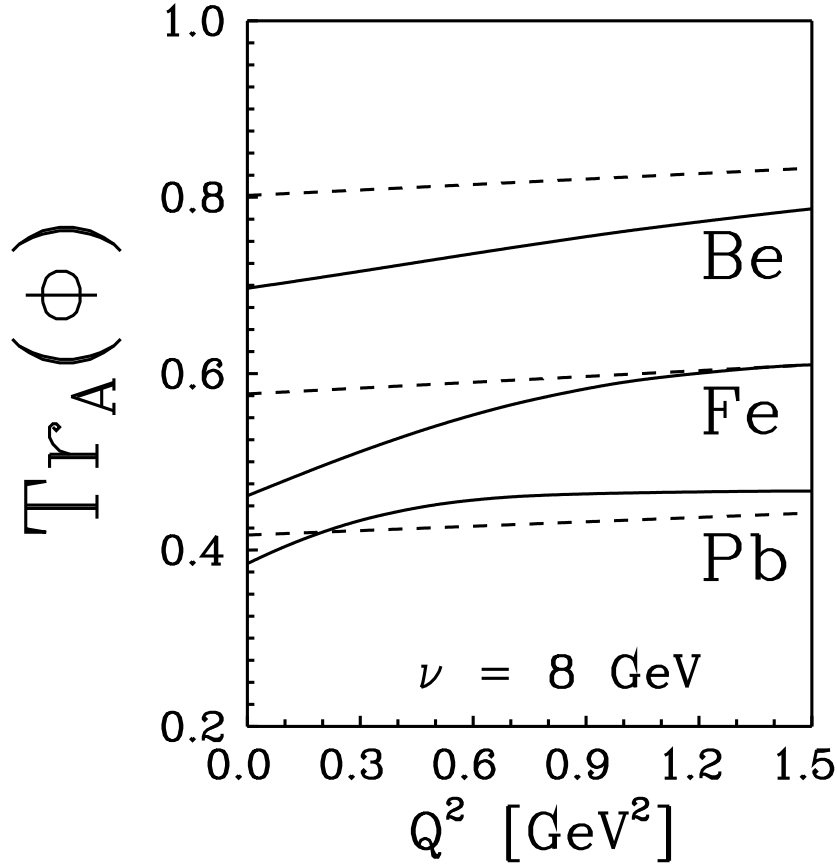
Figure 13: Q^2-dependence of nuclear transparency for incoherent photo-production of ϕ-meson at the photon energies $\nu = 8 \ GeV$. The dashed curves are the results of calculations [36] neglecting the coherence length. The solid curves show our predictions.

depicted in fig. 15a, which contribute to the reaction $\gamma^* p \to V' p$. The second one, containing the off diagonal diffractive amplitude $Vp \to V'p$, cannot be neglected because the photon coupling to V is much larger than to V'. Therefore, the off-diagonal amplitudes $V \rightleftharpoons V'$ should be added to the nuclear multiple scattering series as well, what partially accounts for inelastic corrections to the Glauber approximation.

Let us denote the imaginary parts of the diffractive diagonal and off diagonal amplitudes on a nucleon f_{VV}, $f_{V'V'}$ and $f_{VV'}$. We fix the normalization through the optical theorem, $f_{VV} = \sigma_{tot}^{VN}/2$. We use also the notations from ref. [38], $r_V = f_{V'V'}/f_{VV}$ and $\epsilon_V = f_{VV'}/f_{VV}$.
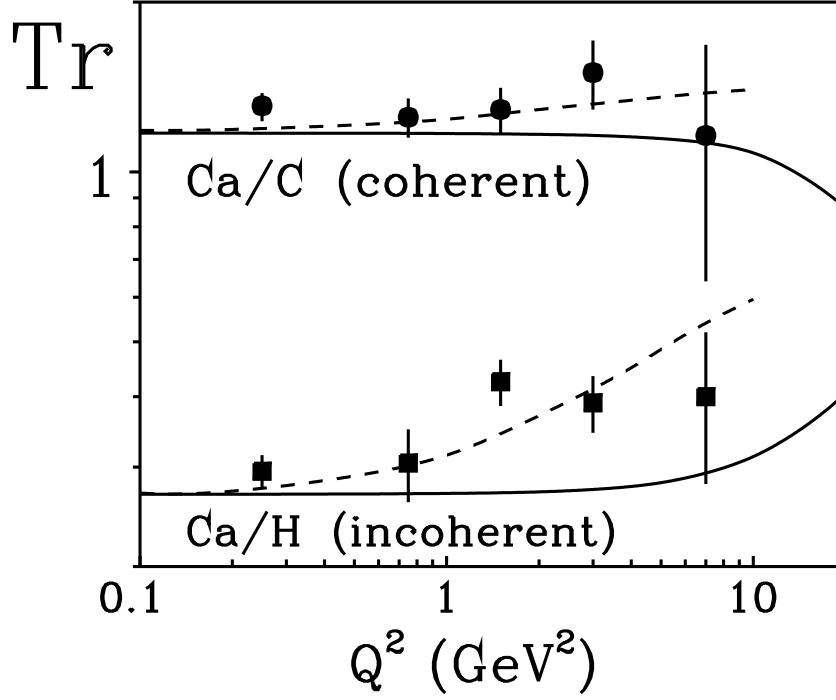
Figure 14: Q^2-dependence of nuclear transparency for coherent (upper points and curves) and incoherent virtual photoproduction of ρ-meson. The solid curves correspond to the Glauber model incorporated coherence length effects. The dashed curves show CT effects predicted for asymptotic energies in [3]. The data points are from the E665 experiment [37]

Then the ratio of the photoproduction amplitude of the radial excitation on a proton given by the diagrams in fig. 15a to that for the ground state shown in fig. 15b reads,

$$
R_{V'/V}(Q^2) = \frac{r_V \left(\dfrac{\Gamma^{l\bar{l}}_{V'} m_V}{\Gamma^{l\bar{l}}_V m'_V}\right)^{\frac{1}{2}} \left(\dfrac{1 + Q^2/m_V^2}{1 + Q^2/m_{V'}^2}\right) + \epsilon_V}{1 + \epsilon_V \left(\dfrac{\Gamma^{l\bar{l}}_{V'} m_V}{\Gamma^{l\bar{l}}_V m'_V}\right)^{\frac{1}{2}} \left(\dfrac{1 + Q^2/m_V^2}{1 + Q^2/m_{V'}^2}\right)} \, , \tag{9}
$$

where $\Gamma^{l\bar{l}}$ is the partial leptonic width of the vector meson.

To calculate the parameters r_V and ϵ_V one needs a dynamical model. For heavy quarkonia one can use the pQCD-based approach, developed in [40],
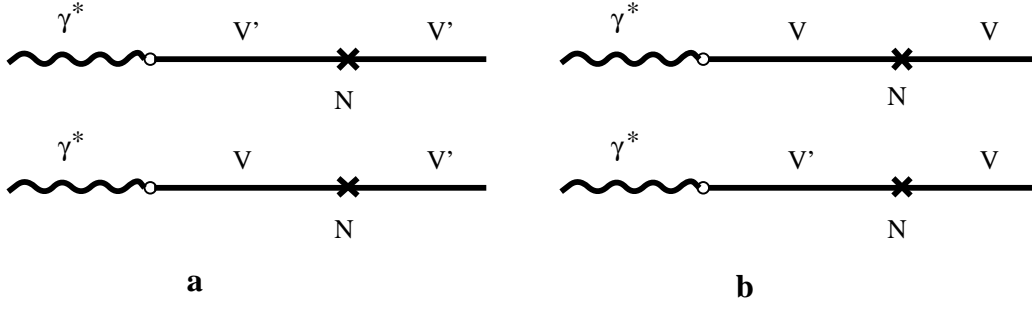
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Figure 15: Diagrams for the virtual exclusive photoproduction of the vector mesons, **a** - the radial excitation V' and **b** - the ground state V, in the two channel approximation

$$f_{V_2 V_1} = \langle V_2 | \sigma(r_T) | V_1 \rangle \equiv \int d^3\vec{r}\; V_2^*(\vec{r}) V_1(\vec{r})\; \sigma(r_T) \tag{10}$$

Here $V_{1,2}(\vec{r})$ are the quark wave function of the initial and the final vector mesons. The flavour-independent dipole cross section, $\sigma(r_T)$, of a $q\bar{q}$ pair interaction with a nucleon depends only on the transverse separation r_T [1]. Due to color screening $\sigma(r_T) \propto r_T^2$ at small r_T, what is a fairly good approximation for heavy quarkonia. Using the nonrelativistic oscillatory model for the wave functions we get [40, 38] $\epsilon_V = -\sqrt{2/3}$ (conventionally $V(0)$ and $V'(0)$ have the same sign) and $r_V = 7/3$. Using these parameters and the data [41] for $\Gamma^{l\bar{l}}_{\Psi'}/\Gamma^{l\bar{l}}_{\Psi}$ we get from eq. (9) $R^2(Q^2 = 0) \approx 0.25$, what is quite close to the measured value $R^2 \approx 0.15 \pm 0.05$ in the real photoproduction [42].

It is interesting that VDM in the form presented in fig. 15 predicts according to eq.(9) for $R^2_{\Psi'/\Psi}(Q^2)$ a Q^2-dependence, similar to what follows from the pQCD based calculations [40],

$$R^2(Q^2) = \left| \frac{\langle V' | \sigma(r_T) | \gamma^* \rangle}{\langle V | \sigma(r_T) | \gamma^* \rangle} \right|^2 , \tag{11}$$

The light-cone wave function of the $q\bar{q}$ component of the photon reads [43],

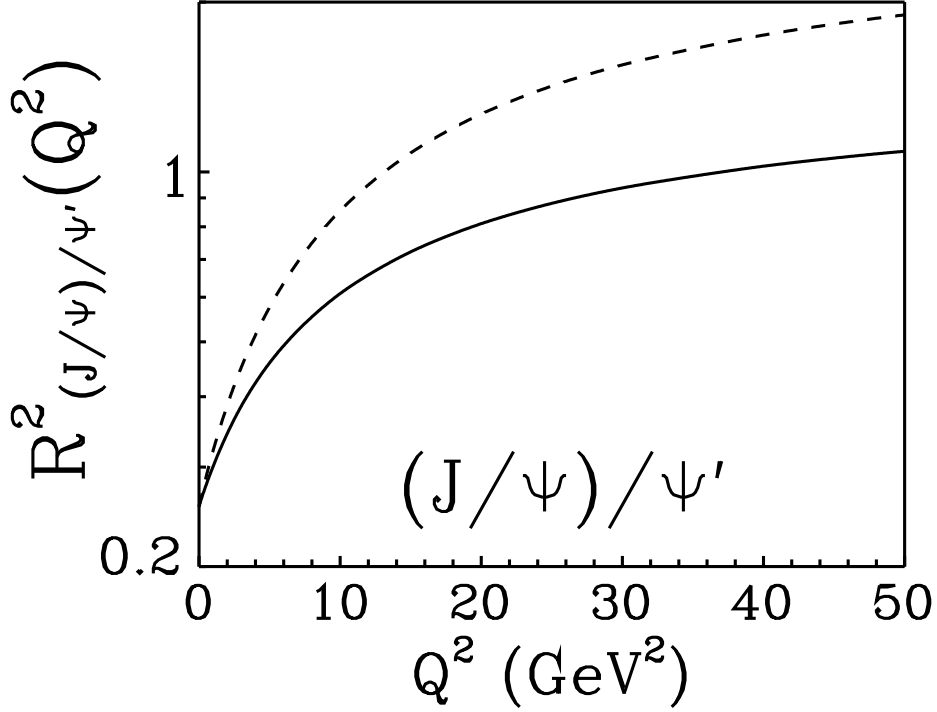$$|\gamma^*\rangle \propto K_0[r_T\sqrt{m_q^2 + Q^2/4}] , \tag{12}$$

Figure 16: Q^2-dependence of the ratio of the production rates of the J/Ψ to Ψ' on a proton. The dashed and solid curves correspond to eqs. (9) and (11) respectively

where K_0 is the modified Bessel function.

Results of calculation of $R^2_{\Psi'/\Psi}(Q^2)$ with eqs. (9) and (11) are presented in fig. 16. The rising Q^2-dependence of R^2 which follows from eq. (11) is usually interpreted in terms of CT [3]: the higher Q^2 is, the smaller is the mean transverse separation $\langle r_T^2 \rangle$ in the produced $q\bar{q}$ wave packet, the less is the influence of the node in the wave function of the radial excitation which provides the suppression of the V' photoproduction [3]. We see that VDM results in a similar and even steeper growth of $R^2(Q^2)$, so an observation of such a behaviour cannot be interpreted as a confirmation of CT.

Situation with the light vector mesons ($\rho'(1450)$, $\omega'(1420)$, $\phi'(1680)$) is less certain. Firstly, the leptonic decay widths are poorly known, or unknown at all. Secondly, the approximation $\sigma(r_T) \propto r_T^2$ is not justified anymore, since large interquark distances are important at low Q^2. Thirdly, the nonrelativistic oscillatory wave functions are too rough approximation for light mesons.

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Our results for the light vector mesons are summarized in Table 1.

TABLE 1. RATIO OF THE V'/V PRODUCTION AMPLITUDES					
Wave function	V-meson	r	ϵ	$\Gamma_{V'}^{l\bar{l}}/\Gamma_V^{l\bar{l}}$	$R^2(V'/V)$
Nonrelativistic	ρ	1.5	-0.5	0.42	0.074
Quark Model	ϕ	1.6	-0.56	0.55	0.290
Relativized	ρ	1.25	-0.14	0.41	0.22
Quark Model	ϕ	1.5	-0.26	0.38	0.28
Experimental	ρ			0.27-0.36	
Data	ϕ			0.35	

In this case the large separations r_T are important and we modify $\sigma(r_T)$ at large distances to incorporate confinement as it is suggested in [43]. Using this dipole cross section and relativized wave functions of ρ- and ρ'-mesons borrowed from ref. [44] we calculated the parameters $\epsilon_\rho = -0.14$ and $r_\rho = 1.25$.

Ratio of the leptonic widths is estimated in the relativistic quark model in ref. [45] at $\Gamma_{\rho'}^{l\bar{l}}/\Gamma_\rho^{l\bar{l}} = 0.064$. Using these values of parameters we predict $R^2_{\rho'/\rho}(Q^2 = 0) \approx 0.005$, what is at least an order of magnitude lower than the measured value [37].

One can try to extract $\Gamma_{\rho'}^{l\bar{l}}$ using available data [41] for different decay channels of ρ'. Combining information on $\eta\rho$ and $\omega\pi$ channels we get $\Gamma_{\rho'}^{l\bar{l}} \approx 1.8 \ KeV$. The data [41] for $\pi\pi$ and $\omega\pi$ decay channels lead to $\Gamma_{\rho'}^{l\bar{l}} \approx 2.4 \ KeV$. As a rough estimate we fix the leptonic partial width at $2 \ KeV$[¶]. Then eq. (9) gives $R^2_{\rho'/\rho}(Q^2 = 0) \approx 0.22$. This value agrees with available data for relative ρ'/ρ photoproduction rates [37], provided that $2\pi^+2\pi^-$ branching is about 10%.

Note, we predict the positive sign for $R_{\rho'/\rho}(Q^2 = 0)$ what is different from pQCD estimation in refs. [3, 22] which use formula (11). In the latter case the negative sign of R results from "overcompensation" of the large-r_T part of the ρ' wave function compared to the short distance part. As a consequence, a change of sign of $R(Q^2)$, i.e. a sharp minimum

[¶]similar value of $\Gamma_{\rho'}^{l\bar{l}}$ was found from the analyses [46]

in Q^2-dependence of R^2 at $Q^2 \approx 0.3 \ GeV^2$ was predicted in [22]. Such an approach is based on the pQCD evaluation of the photon wave function. We work here in the hadronic basis and use experimental data for most important low-mass states.As is different from [22] we expect a smooth monotonous increase of $R^2_{\rho'/\rho}$ as a function of Q^2 as is shown in fig. 17 together with the preliminary data from the E665 experiment [37]. Again, the predicted Q^2-dependence of R^2 originates from VDM and should not be misinterpreted as an evidence of CT. Important is only the negative sign of $f_{VV'}$ which is associated with any reasonable model, which predicts a rising r_T-dependence of $\sigma(r_T)$.
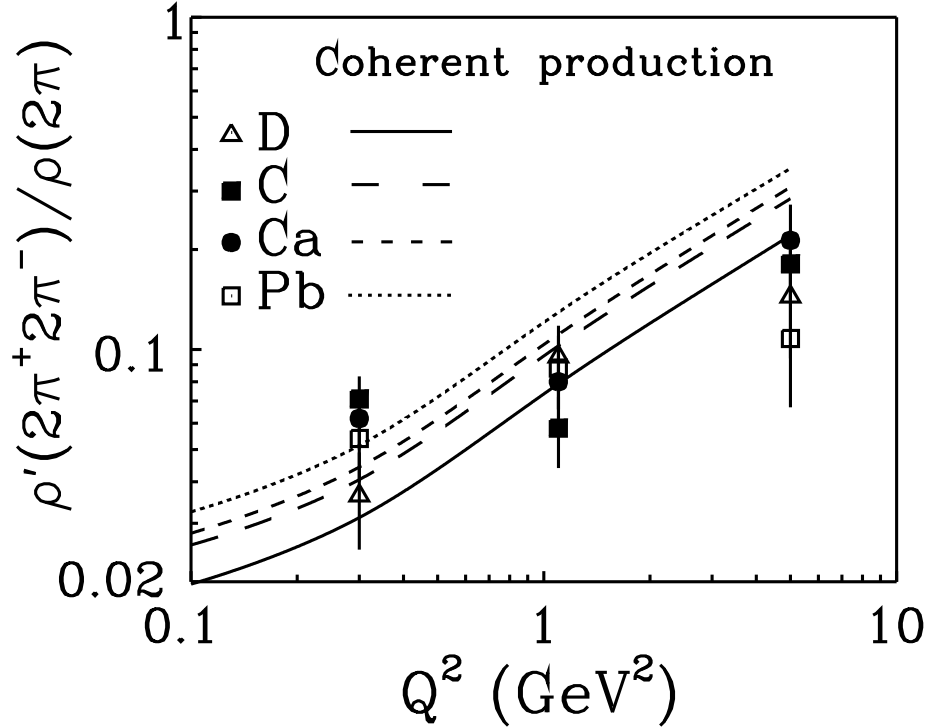

Figure 17: Q^2-dependence of the ratio of coherent photoproduction rates of ρ' to ρ on different nuclei. The curves correspond to the two-channel VDM model incorporating coherence length effects. The data points are from the E665 experiment [37]

We use experimental information on $\gamma \to \rho$ and $\gamma \to \rho'$ couplings, which seems to to provide more reliable predictions than that in [3, 22] where the wave function of the $q\bar{q}$ fluctuation of the photon was estimated in the nonrelativistic quark model neglecting the interquark interaction potential.

Using the same procedure we estimate the diffractive amplitudes for ϕ and ϕ' interaction, $\epsilon_\phi = -0.26$, $r_\phi = 1.5$.

5 Nuclear effects in electroproduction of the radial excitations

As soon as we included in the consideration production of the radial excitations, we are enforced to consider the production and the propagation through the nucleus of a wave packet which is a linear combination of V and V'. Corresponding approach was developed and used in refs. [18, 16, 19, 20, 38]. The evolution equation for the wave packet $|\Psi(z)\rangle = \binom{V}{V'}$ propagating through the nuclear matter has a form of the Schrödinger equation,

$$i\frac{d}{dz}|\Psi(z,\vec{b})\rangle = \widehat{U}(z,\vec{b})|\Psi(z,\vec{b})\rangle \ , \tag{13}$$

The evolution operator can be represented in the form $\widehat{U} = \hat{q} - i\hat{f}\ \rho(b,z)$, where

$$\widehat{q} = \begin{pmatrix} q_L & 0 \\ 0 & q'_L \end{pmatrix} \tag{14}$$

$$\widehat{f} = \frac{\sigma_{tot}^{VN}}{2}\begin{pmatrix} 1 & \epsilon \\ \epsilon & r \end{pmatrix} \tag{15}$$

All quantities here were defined above. except $q'_L = (Q^2 + m_V'^2)/2\nu$.

It is interesting that the parameters r, ϵ and R^2 which we found in the previous section for real photoproduction of charmonia, are just those magic values [38], which correspond to the production in the initial state a combination of J/Ψ and Ψ', which is the eigen state of interaction. Such a wave packet propagates through the nuclear matter with constant relative content of J/Ψ and Ψ'. This means, that nuclear suppression is the same for Ψ' and J/Ψ. This surprising effect was observed in hadroproduction of charmonia [39] and explained in [38]. Now we expect the same for the real photoproduction. A stronger relative enhancement of the Ψ' photoproduction on nuclei was predicted in [40]. That approach has an advantage of using the path-integral technique, what is equivalent to the

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general multichannel consideration. However it relays upon the projection to the quark wave function of the photon in the form of eq. (12). We use the experimental data for $\Gamma^{l\bar{l}}_{\Psi'}/\Gamma^{l\bar{l}}_{J/\Psi}$ at this point. Note, whatever prediction is correct, the principal is the coupled-channel approach for propagation of the charmonium in the medium, first developed in [40].

We have solved evolution equation (13) numerically for the realistic nuclear density distribution [21]. We used the experimendal data for $\Gamma^{l\bar{l}}_{V'}/\Gamma^{l\bar{l}}_{V}$ and the parameters r and ϵ corresponding to the relativized quark model in Table 1. The results for coherent production of ρ, ρ' and ϕ, ϕ' are shown by the solid curves in figs. 18 and 19 respectively. Predictions of the eikonal Glauber approximation are plotted by the dashed curves for comparison.
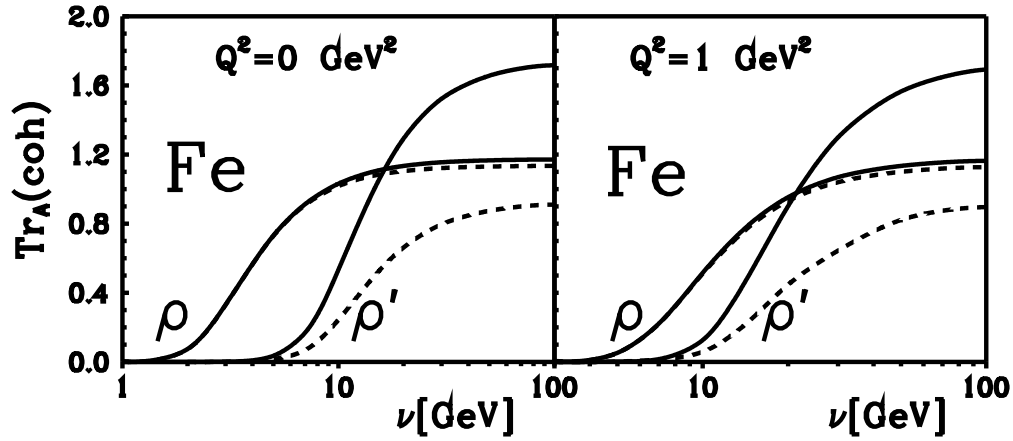

Figure 18: Comparison of the Glauber model prediction (dashed curves) with the prediction of the two-channel approach (solid curves) for the nuclear transparency in the coherent electroproduction of the ρ- and ρ'-mesons on iron as function of energy

We see that the addition of the off-diagonal diffractive amplitudes $V \rightleftharpoons V'$ to the eikonal approximation results in a miserable correction to the nuclear transparency for the ground states. However, it leads to a dramatic enhancement of nuclear transparency for the radial excitations. This is easily interpreted as a result of the weakness of the relative production rate of the radial excitations on a proton. In this case the off-diagonal amplitude $\gamma \rightarrow V' \rightarrow V$ turns out to be suppressed twice compared with $\gamma \rightarrow V \rightarrow V$, so the production of the ground states gains a tiny distortion. On the other hand, for production of the radial
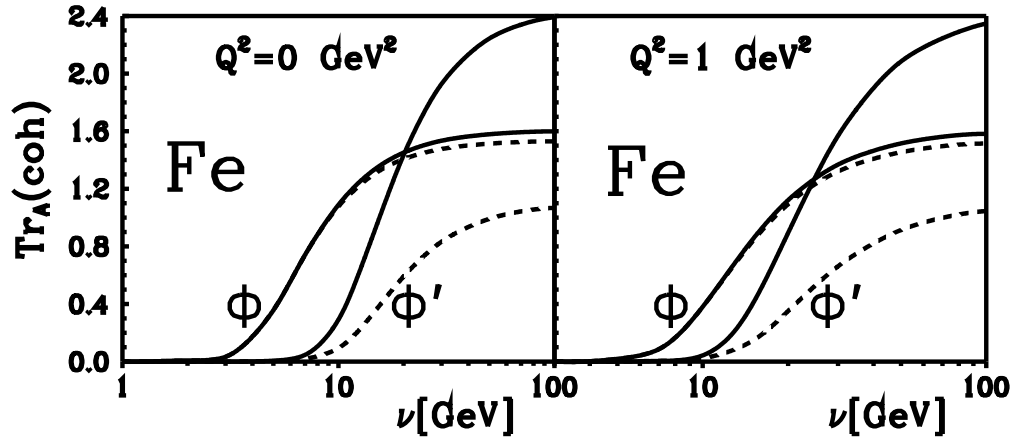
Figure 19: The same as in fig. 18 for the electroproduction of ϕ- and ϕ'-mesons

excitation V' the main correction comes from the off-diagonal amplitude $\gamma \to V \to V'$, which is enhanced compared to the diagonal one $\gamma \to V' \to V'$. This is the main source of the abnormal nuclear enhancement of the photoproduction of the radial excitations of the vector mesons, discovered in [40]. Note that this effect is usually considered as a manifestation of CT effects, however, we see that it may have quite a simple origin.

We have restricted our consideration in this section with a simplest case of coherent productions. Evolution equation can be used for incoherent production at the same footing, and its generalization to a multichannel case is not difficult. Those results will be published elsewhere.

6 Conclusions

In present paper we consider the typical reactions with electron beams, which are under an intensive discussion recent years as an effective way to search for CT. However, we try here to be maximally free of color dynamics and CT effects and we do that *on purpose*. We either stay with the standard eikonal Glauber model incorporated with the coherence length effects, or we go beyond this approximation, but include only those corrections which do not contain an explicit color dynamics. This is to provide a better *baseline* for searching for CT

effects. We came to conclusion that at moderate electron energies the standard mechanisms lead sometimes to the effects which are usually expected to be a signature of CT, or at least of its onset.

If the authors of ref. [12] had been asked 20 years ago to repeat their calculations, properly modified to predict Q^2-dependence of nuclear transparency in $(e, e'p)$ reaction, they would have provided the prediction similar to what is depicted in fig. 3. It is quite probable that such a behaviour will be observed soon in future experiments at CEBAF, HERMES, ELFE. However, one should be cautious interpreting it as a signal of CT.

Existing proposals [47, 48] to study CT effects in electroproduction of vector mesons at CEBAF or HERMES rely upon the predictions [3] which were done for asymptotic-energies. However, the energy range of interest is most sensitive to another effect associated with the energy- and Q^2-variation of the coherence length. This results in dramatic changes of the nuclear transparency even within the standard Glauber approximation. The formula for incoherent virtual photoproduction of vector mesons, which is valid through the whole energy range, was unknown before. We predict a variation of nuclear transparency up to a few hundred percents for heavy nuclei, as a function of the energy or virtuality of the photon. These effects easily mock CT in the incoherent productions, and anyway should be taken into account to predict the baseline for CT.

In the case of virtual photoproduction of the radial excitations we use the two-channel VDM approximation which provides a Q^2-dependence of relative yields of V' to V and the nuclear antishadowing similar to what is supposed to result from the color dynamics of interaction, namely, from decreasing Q^2-dependence of the transverse separation of the photoproduced $q\bar{q}$ wave packet.

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